TITLE OF THE INVENTION

METHOD AND APPARATUS FOR INSPECTING AN EUV MASK BLANK

CROSS-REFERENCE TO RELATED APPLICATIONS

5 Not Applicable

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

OR DEVELOPMENT

REFERENCE TO A MICROFICHE APPENDIX

Not Applicable

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BACKGROUND OF THE INVENTION

1. <u>Field of the Invention</u>

The present invention pertains generally to extreme ultraviolet lithography

(EUVL), and more particularly to at-wavelength inspection of reflective multilayer-coated

20 mask blanks.

2. <u>Description of the Background Art</u>

Reflective extreme ultraviolet light (EUV) mask blanks, which are fabricated and

subsequently patterned, are becoming critical elements in a relatively new photolithographic technology that incorporates EUV light. Mask blanks are formed from large (e.g., typically greater than four-inch square or diameter) substrates coated with a spatially uniform, reflective multilayer structure. The fabrication tolerances for

5   lithographic quality mask blanks require reflectivity uniformity in the range of ±0.1%, and centroid wavelength variation of a few tenths of an angstrom. The success of this technology therefore relies on the development of metrology tools capable of accurately and efficiently measuring large numbers of mask blanks, both for the qualification of the mask blanks and the tools that produce them.

10   The characterization of a large number of EUV mask blanks has been an essential aspect of the calibration of various multilayer deposition tools, and in the cross-correlation of different multilayer characterization systems. In the current state of the art, when the coating uniformity is to be assessed, a narrowed EUV beam is focused to a relatively small spot on the mask. A suitable detector or detectors

15   measures the power of the reflected beam, from which the reflectivity is calculated. During the measurement, a number of parameters may be varied, including the position of the measurement, the angle of incidence and the wavelength of the illumination. From these measurements, the multilayer d-spacing, Γ parameter, and centroid- or peak-of-reflectivity wavelength may be determined.

20   The spatial dependence of the multilayer parameters is measured one spot at a time, in series. The size of the radiation spot on the mask blank controls, to some extent, the spatial resolution of the measurement. Where the spot is small, concern

may arise that a sparse sampling of measurement positions on the mask may miss significant features. On the other hand, where the spot is relatively large, it may average together high- and low-quality regions producing results that may not characterize the sample well.

5   Therefore, there is a need for a method and apparatus for characterizing a large number of EUV blanks that is well suited for inspection of moderate and low spatial frequency coating uniformity. The present invention satisfies those needs, as well as others, and overcomes deficiencies in conventional approaches.

BRIEF SUMMARY OF THE INVENTION

10   The present invention pertains to a fast, large area, course preliminary inspection system for mask blank used in EUV lithography. By way of example, and not of limitation, the system comprises an EUV light source such as a synchrotron that directs a beam of light to a reflective mask blank, and an EUV detector such as a mega-pixel CCD camera array or micro-channel plate positioned to record the reflection from a

15   relatively large area (i.e., multiple spots) of the mask blank in a single exposure. The system provides a 1:1 mapping of a large area of the mask blank, where each pixel in the array corresponds to a small area on the mask blank. This ability of the system to simultaneously record multiple spots of the mask blank provides for a faster inspection than conventional point by point inspection of small areas on the mask blank.

20   By adjusting the distance between the CCD camera array and the mask blank, an EUV light source that directs a beam of light to a mask blank, and an EUV detector such as a CCD camera array or micro-channel plate positioned to record the reflection

from a relatively large area of mask blank in a single exposure. The size and position of EUV light source, as well as the size and position of the CCD camera array, determine the illumination area on mask blank and the area that can be inspected.

An object of the invention is to inspect EUV mask blanks for lithographic quality tolerances.

Another object of the invention is to detect any kind non-uniformity that may arise in the reflectivity of multi-layer mirrors.

Another object of the invention is to determine if an EUV mask blank has a reflectivity uniformity in the range of ±1%.

Another object of the invention is to determine if an EUV mask blank has a centroid wavelength variation of a few tenths of an angstrom.

Another object of the invention is to accurately and efficiently inspect large numbers of EUV mask blanks.

Another object of the invention is to inspect a large area on an EUV mask blank in a single exposure to an EUV light source.

Further objects and advantages of the invention will be brought out in the following portions of the specification, wherein the detailed description is for the purpose of fully disclosing preferred embodiments of the invention without placing limitations thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood by reference to the following drawings which are for illustrative purposes only:

FIG. 1 is a schematic diagram of a mask blank inspection apparatus according to the present invention.

FIG. 2 is a schematic diagram of the mask blank inspection apparatus shown in FIG. 1 with the EUV detector reposition for inspecting a larger area of a mask blank.

FIG. 3 is a detailed schematic diagram of the apparatus shown in FIG. 1.

FIG. 4 is a detailed schematic diagram of the apparatus shown in FIG. 2.

FIG. 5A through FIG. 5F are graphs showing the results of defect visibility simulation for various defect sizes based on the configuration shown in FIG. 3.

FIG. 6 is a schematic diagram of an embodiment of a mask blank inspection apparatus according to the invention that employs a detector for measuring the illumination pattern of the EUV light source.

DETAILED DESCRIPTION OF THE INVENTION

The invention will now be described with reference to FIG. 1 through FIG. 6, where like reference numbers denote like parts. It will be appreciated that the apparatus may vary as to configuration and as to details of the parts, and that the method may vary as to the specific steps and sequence, without departing from the basic concepts as disclosed herein.

Referring first to FIG. 1 and FIG. 2, an apparatus 10 for inspecting mask blanks for defects according to the present invention is shown. As used herein, the term

"defect" is intended to encompass any kind of non-uniformity that may arise in the reflectivity of multi-layer mirrors. As can be seen, the apparatus comprises an EUV light source 12, such as a synchrotron or the like, that directs a beam of light 14 to a mask blank 16, and an EUV detector 18 such as a CCD camera array or micro-channel plate

5 positioned to record the reflection 20 from a relatively large area of mask blank 16 in a single exposure. Mask blank 16 is typically a large (e.g., four-inch or greater square or diameter) polished substrate coated with a spatially uniform, reflective multilayer structure as commonly used in EUV lithography.

FIG. 1 and FIG. 2 show two configurations of the apparatus for inspecting small

10 22 and large 24 areas, respectively, where the angles and sizes shown are greatly exaggerated for heuristic reasons. Note that the size and position of EUV light source 12, as well as the size and position of EUV detector 18, determine the illumination area on mask blank 16 and the area that can be inspected. Additionally, EUV light source 12 should preferably have uniform, or well characterized illumination across the

15 measurement area of mask blank 16.

Note the simplicity of the configurations shown in FIG. 1 and FIG. 2. The apparatus requires only two elements; namely, EUV light source 12 and the EUV detector 18, that are positioned in relation to mask blank 16. Furthermore, translation of mask blank 16 in a fixed measurement plane will enable the apparatus to probe and

20 measure an arbitrarily large area of mask blank 16 in a single exposure. The angle of incidence 26 of mask blank 16 may also be adjusted to probe the angular dependence of the reflectivity. It will be appreciated, therefore, that rotation of the angle of mask

blank 16 accompanied by appropriate re-positioning of the source or detector, or variation of the wavelength of EUV light source 12, enables the study of the multilayer parameters. In its default position, EUV detector 18 can remain fixed at an angle 28 normal to the central ray, which angle is preferably twice the inclination angle 26 of mask blank 16.

Referring now to FIG. 3 and FIG. 4, schematic scale drawings of the exemplary embodiments of the configurations shown in FIG. 1 and FIG. 2, respectively, can be seen. In FIG. 3 and FIG. 4, the EUV source beam 14 is directed through a pinhole filter 30 to provide a beam with an illumination angle corresponding to a numerical aperture (NA) of approximately 0.008, which is an appropriate value for spatially filtered light from an ALS undulator beamline 12.0.1.2. In FIG. 3, pinhole filter 30 and EUV detector 18 are positioned axially from mask blank 16 by 32.25 inches, the beam center of EUV detector 18 is 5.5 inches above the beam center of EUV beam 14, and angle of incidence 26 is five degrees. In FIG. 4, pinhole filter 30 is positioned 47.5 inches from mask blank 16, EUV detector 18 is positioned 15.5 inches from mask blank 16, EUV detector 18 is 2.65 inches above EUV beam 14, and angle of incidence 26 is five degrees.

As can be seen by comparing FIG. 4 with FIG. 3, moving mask blank 16 farther from EUV source 12 and bringing EUV detector 18 closer creates a larger single-exposure measurement area. In the example shown in FIG. 3, EUV detector 18 is one-inch square, the single-exposure measurement area 22 is 0.5 inches and a δ-fn defect appears 300 μm wide (12 pixels where pixel size is 25 μm). In contrast, in the example

shown in FIG. 4, EUV detector 18 is one-inch square, the single-exposure

measurement area 24 is 0.75 inches and a δ-fn defect appears 180 μm wide (7 pixels).

While FIG. 1 through FIG. 4 show preferred geometries of the apparatus, it will

be appreciated that a wide range of geometries can be employed. This requires

5   consideration of the following factors:

1.   Measurement Area.

It will be appreciated that the path of rays from EUV light source 12 to EUV

detector 18 determines the measurement area on the mask, independent of the source

divergence. In general, the closer the detector is placed to the mask, the closer the

10   measurement area becomes to the size of the detector. Moving the detector farther

away from the mask produces a greater geometric magnification, and reduces the size

of the measurement area. For example, in the configuration of FIG. 3, with a one-inch-

square detector array, the measurement area will be in the range of 0.5 inches square

as described above, while in the configuration of FIG. 3, the measurement area will be

15   in the range of 0.75 inches square.

2.   Angular Range.

Because multilayer reflectivity is sensitive to the angle of incidence, it is often

desirable to illuminate the sample with a collimated beam, or a beam of limited solid

angle. In the configurations shown in FIG. 1 through FIG. 4, it will be appreciated that a

20   range of incident angles is unavoidable. However, with a diverging source, the sample

may be moved an arbitrary distance away from the source, and EUV detector 18

repositioned to reduce the solid angle of the measurement area to any value.

Dependent strongly on the properties of EUV light source 12, this extra distance may reduce the illumination intensity and increase the exposure time. For example, assuming a one-half inch square measurement area, and using the edges of the square domain, the range of incident angles seen on the mask varies as a function of distance,

5   D, as follows:

$$\theta = \pm \frac{1/2"}{D} = \pm \frac{1}{2D} \tag{1}$$

Table 1 shows various values of θ as a function of distance:

3.   <u>EUV Source.</u>

EUV light source 12 should preferably be able to uniformly illuminate the

10   measurement area, or have an illumination pattern that can be measured and calibrated. For example, for a synchrotron beamline light source, this generally means that the illumination must be spatially filtered to produce a relatively uniform beam profile. The use of a laser-produced plasma source, a discharge lamp, or another non-synchrotron source must be evaluated on a case-by-case basis. Considering the

15   angular range described above, it may be advantageous to use an EUV light source with a small divergence angle to achieve reasonable efficiency and utilize as much of the available light as possible.

4.   <u>Spatial Resolution.</u>

It will be further appreciated that the resolution of the invention is limited by

20   diffraction, which depends on the wavelength, and a combination of the distance from EUV light source 12 to mask blank 16 and the distance from EUV detector 18 to mask

blank 16. Because a large area of the mask sample is illuminated, localized, very small defects may fall below the sensitivity of the apparatus, except possibly in extreme cases. On the other hand, localized defects of slightly larger size will be visible by their shadow in the recorded image, and/or by interference fringes which they produce. The ability of the apparatus to produce fringes, in a way equivalent to an in-line hologram, depends largely on the spatial coherence of the illumination at the sample, which in turn depends on the size, position, and coherence of the source.

Simple calculations shown that the minimum resolvable feature sizes will be on the order of 100 μm to 200 μm for high-contrast amplitude or phase objects. FIG. 5A through FIG. 5F show the results of simple defect visibility simulations based on the geometry of FIG. 3 with equal source-to-mask and mask-to-CCD distances. A range of defect sizes from 20 μm to 600 μm was investigated. Below 100 μm it was found that the defects appear to have nearly the same lateral size, but the amplitude of the observed intensity variation depends on the size of the defect; that is, its diffracting strength. Because we are considering a defect illuminated by a spherical wavefront, the phase variation of the light hitting the defect plays a role. As can be expected, above 300 μm diameter, the observed size of the diffraction pattern begins to follow the increasing size of the defect.

5.   Exposure Time.

The exposure time depends on several critical parameters; namely, photon flux from EUV light source 12 into the solid angle of measurement F (ph/s), sensitivity c (counts per incident photon) of EUV detector 18, the array width W (pixels) of EUV

detector 18, the reflectivity R of mask blank 16, and the required signal-to-noise ratio s.

For example, assume a desired sensitivity s of 0.1% at each measurement point

in the area of measurement. Based on Poisson statistics, measurement with this

5   signal-to-noise ratio requires $\dfrac{1}{s^2} = \dfrac{1}{(10^{-3})^2} = 10^6$ photons at each point. With a detector

sensitivity c of five counts per incident photon, this indicates that 5×10^6 counts per

measurement point are needed. Using a 16-bit CCD camera array (up to $2^{16} = 65536$

counts per pixel) for EUV detector 18, we would need to gather the signal from $\dfrac{c}{s^2 2^{16}} =$

$\dfrac{5 \times 10^6}{65536} = 76$ pixels. To achieve this, assume that we collect the signal from the CCD

10   array and bin or group the data into squares of width greater than $\sqrt{\dfrac{c}{s 2^8}} = \sqrt{76} \approx 9$. For

this calculation, 10 pixel x 10 pixel squares should suffice. In a W x W = 1024 pixel x

1024 pixel array, there are $\dfrac{W^2 s^2 2^{16}}{c} \approx \left(\dfrac{W}{10}\right)^2 = 10{,}400$ such 10 x 10 squares, each

receiving 10^6 incident photons, for a granted total of $\dfrac{W^2 2^{16}}{c} \approx 1 \times 10^{10}$ photons per

exposure. The exposure time is therefore given by the number of photons per exposure

15   divided by the source's photon flux into the solid angle of measurement, divided by the

reflectivity, as follows:

$$\frac{W^2 2^{16}}{FRc} \, .$$

For ALS beamline 12.0.1.2, using a 0.75 μm spatial filter pinhole 30, the predicted exposure time per measurement is approximately $1/40^{th}$ second ($F \approx 8 \times 10^{11}$ photons/second). For ALS beamline 11, a bending magnet source, and $F \approx 8 \times 10^{9}$ photons/second, the predicted exposure time per measurement is 2.5 seconds. For the proposed next generation of EUV lithography sources, with collectable power output in the range of 10 Watts, $F \approx 10^{18}$ photons/second and the predicted exposure time per measurement is 2×10^{-8} seconds to achieve a 0.1% signal-to-noise ratio (SNR). In that case, the measurement time limitation becomes the camera read-out and data processing, and the overhead related to the stage motion. The time required to cover an 8-inch mask blank may be computed by the given times scaled upward by the ratio of the total area to the measurement area.

With 25 μm square pixels, the effective resolution of the detector becomes 250 μm after 10x10 binning. This corresponds to an area of approximately 125 μm on the mask, a size scale consistent with the stated resolution of the apparatus determined by diffraction.

With foregoing in mind, we now address a number of considerations for making measurements with this apparatus.

1.   Redundant Measurement.

To inspect large mask areas, the mask position preferably must be scanned, or advanced in discreet steps. To improve the signal-to-noise ratio and reduce measurement uncertainties from calibration, it may be useful to advance the mask position by a distance smaller than the single-step measurement area. At the expense

of measurement time, this technique allows a given point on the mask to be illuminated

from different positions and with different angles in the measurement area. By keeping

track of positions on the mask and observing the reflected intensity multiple times at

each mask point, the effects of illumination non-uniformities can be reduced or even

5   studied. Furthermore, if the angular variation across the measurement area is large

enough, moving the sample effectively scans the illumination angle seen by each point.

To enhance this effect, the sample could be inclined so that the ideal illumination angle

occurs not at the center of the field but rather at the edge. In this configuration, each

snapshot of the reflected intensity shows a range of incidence angles.

10   2.   Geometric Calibration.

In order to calibrate the motion of the wafer-translation stage, preferably we set

the position and angle of EUV detector 18, and adjust the alignment of the illuminating

beam. One approach is to inspect a patterned mask blank. A non-reflecting pattern on

the reflective surface may be a course grid of lines or dots that are visible (spatially

15   resolvable) by EUV detector 18. The use of recognizable alignment marks could help in

identifying specific patterns or locations on the mask. Misalignment of EUV detector 18

(including angular tilts) may be judged by measuring inhomogenaities in the observed

pattern. To make these adjustments possible, it may be necessary to mount EUV

detector 18 on a bellows or other flexible section of a vacuum chamber.

20   3.   Source Non-Uniformity.

Where the uniformity of EUV light source 12 is a concern, the illumination pattern

can be measured directly an EUV detector in a different position, an example of which is

shown in FIG. 6. With mask blank 16 removed, light will fall directly onto a second EUV detector 32, which again is a CCD camera array or the like, which records the angular distribution of EUV light source 12. If necessary, this information can be used to calibrate the recorded intensity pattern of the light reflected from the masks. If long-term source stability is a concern (as it may be with a spatially filtered beam) the two EUV detectors 18, 32 can be used at all times. EUV detector 18 would be used for the reflection measurement, and EUV detector 32 would be used for illumination measurement. Mask blank 16 may simply be removed from the beam path to allow the straight-through light to reach EUV detector 32 at any time. EUV detector 32 may also be moved closer to the mask position if space is limited.

4.   Non-Tunable Source.

If EUV light source 12 is not tunable, the multilayer parameters may be calculated from the measurement of the angular dependence of the reflectivity. In this situation the angle of the mask blank 16 should be adjustable. It may be preferable to rotate the mask about an axis perpendicular to the plane containing the illumination's central ray and its reflection. Due to the change in geometry as the top and bottom portions of the illuminated mask area move closer or farther from EUV detector 18, additional geometric calibration may be required for proper analysis.

5.   Extreme Simple Implementation.

One essential characteristic of a uniform mask blank is that the reflectivity has no spatial variation. Without calibrating the illumination angles, the EUV light source intensity distribution, the EUV detector geometry or even the illumination wavelength,

one could translate a sample in-plane during measurement and simply look either for

spatial non-uniformities, or a measurable difference from a well-calibrated mask blank

used as a reference. Because the multilayer reflectivity varies slowly near the peak (as

a function of angle, or wavelength) to increase the sensitivity of the measurement, the

5   apparatus could be operated intentionally off-peak. Here again, spatial variations in the

reflected intensity could be observed.

Although the description above contains many specific implementations, these

should not be construed as limiting the scope of the invention but as merely providing

illustrations of some of the presently preferred embodiments of this invention.

10   Therefore, it will be appreciated that the scope of the present invention fully

encompasses other embodiments which may become obvious to those skilled in the art,

and that the scope of the present invention is accordingly to be limited by nothing other

than the appended claims, in which reference to an element in the singular is not

intended to mean "one and only one" unless explicitly so stated, but rather "one or

15   more." All structural, chemical, and functional equivalents to the elements of the above-

described preferred embodiment that are known to those of ordinary skill in the art are

expressly incorporated herein by reference and are intended to be encompassed by the

present claims. Moreover, it is not necessary for a device or method to address each

and every problem sought to be solved by the present invention, for it to be

20   encompassed by the present claims. Furthermore, no element, component, or method

step in the present disclosure is intended to be dedicated to the public regardless of

whether the element, component, or method step is explicitly recited in the claims. No

claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth

paragraph, unless the element is expressly recited using the phrase "means for."

Table 1

D (inches)	D (cm)	θ (mrad)	θ degrees
10.000	25.400	±50.000	±2.865
20.000	50.800	±25.000	±1.432
50.000	127.000	±10.000	±0.573
100.000	254.000	±5.000	±0.286